PLANAR INVERTED F ANTENNAS INCLUDING CURRENT NULLS BETWEEN FEED AND GROUND COUPLINGS AND RELATED COMMUNICATIONS DEVICES

FIELD OF THE INVENTION

The present invention relates to the field of antennas, and more particularly to planar inverted F antennas and related communications devices.

BACKGROUND

The size of wireless terminals has been decreasing with many contemporary wireless terminals being less than 11 centimeters in length. Correspondingly, there is increasing interest in small antennas that can be utilized as internally mounted antennas for wireless terminals. Inverted-F antennas, for example, may be well suited for use within the confines of wireless terminals, particularly wireless terminals undergoing miniaturization. Inverted-F antennas may provide small size, low cost, and mechanical robustness. Typically, conventional inverted-F antennas may include a conductive element that is maintained in a spaced apart relationship with a ground plane. Exemplary inverted-F antennas are described, for example, in U.S. Patent Nos. 5,684,492 and 5,434,579, which are incorporated herein by reference in their entirety.

Furthermore, it may be desirable for a wireless terminal to operate within multiple frequency bands in order to utilize more than one communications system. For example, Global System for Mobile communication (GSM) is a digital mobile telephone system that typically operates at a low frequency band, such as between 880 MHz and 960 MHz. Digital Communications System (DCS) is a digital mobile telephone system that typically operates at high frequency bands, such as between 1710 MHz and 1880 MHz. In addition, global positioning systems (GPS) or Bluetooth systems may use frequencies of 1.575 or 2.4-2.48 GHz. The frequency bands allocated for mobile terminals in North America include 824-894 MHz for Advanced Mobile Phone Service (AMPS) and 1850-1990 MHz for Personal Communication Services (PCS). Other frequency bands are used in other jurisdictions. Accordingly, internal antennas are being provided for operation within multiple frequency bands.

Figure 9 illustrates one example of a prior art PIFA (planar inverted "F" antenna) that uses a center signal fed planar antenna shape with capacitive coupling **10**. Generally stated, the high band element has an end portion that typically capacitively couples to a closely spaced apart end portion of the low band element, which, in operation, may cause a larger portion of the antenna element to radiate. U.S. Patent No. 6,229,487 describes similar configurations for wireless devices, the contents of which are hereby incorporated by reference as if recited in full herein. Unfortunately, the increase in the coupling between the two elements by this configuration may result in degradation in bandwidth at the low-band element. In addition, the parasitic element may dictate tight manufacturing tolerances for proper operation that may increase production costs.

Kin-Lu Wong, in *Planar Antennas for Wireless Communications*, Ch.1, p. 4, (Wiley, Jan. 2003), illustrates some potential radiating top patches for dual-frequency PIFAS. As shown, the PIFA in Figure 1.2(g) has a plurality of bends, but the configuration is such that the capacitive coupling between the two branches (primary and secondary branches) may be relatively large.

Certain antenna configurations may be used to increase operating efficiency. One such configuration, for example, is discussed by Mads Sager *et al.* in "A Novel Technique To Increase The Realized Efficiency Of A Mobile Phone Antenna Placed Beside A Head-Phantom" (IEEE 2003), the disclosure of which is hereby incorporated herein by reference in its entirety. Sager *et al.* discloses a dual-band PIFA antenna mounted on the backside of a printed circuit board, and a parasitic radiator mounted on the front side of the printed circuit board. Despite the foregoing, there remains a need for alternative planar antennas.

SUMMARY

According to embodiments of the present invention, a planar inverted F antenna may be configured for operation at an operating frequency band. The planar inverted F antenna may include three antenna segments, a reference voltage coupling, and a feed coupling. The first and second antenna segments may be separated by at least approximately 3 mm, and the third antenna segment may couple the first and second antenna segments. The reference voltage and feed couplings may be provided on the first antenna segment, and a current null may be present between the feed and reference voltage couplings at the operating frequency band.

The feed and reference voltage couplings may be separated by at least approximately 15 mm, and the first and second antenna segments may be rectilinear and parallel. Moreover, the third antenna segment may be coupled to the first and second antenna segments at ends of the first and second antenna segments. In addition, the feed coupling may be spaced apart from the third antenna segment by a greater distance than the reference voltage coupling, and the first and the third antenna segments may define an angle of approximately 90 degrees.

The first antenna segment (including the feed and reference voltage couplings) may be longer than the second antenna segment. Moreover, the operating frequency band may be in the range of approximately 1700 MHz to 2500 MHz. In addition, a printed circuit board may include a reference voltage conductor and an antenna feed conductor, and the reference voltage coupling may be electrically coupled to the reference voltage conductor of the printed circuit board and the feed coupling may be electrically coupled to the antenna feed conductor. The reference voltage coupling may be electrically coupled to the reference voltage conductor through an electrical short or through a non-zero impedance. In addition, the operating frequency band may include a high-frequency band and a low-frequency band, the current null may be present between the feed and reference voltage couplings at the high-frequency band, and the current null may not be present between the feed and reference voltage couplings at the low-frequency band.

According to additional embodiments of the present invention, a planar inverted F antenna may include a conductive antenna element, a feed coupling on the conductive antenna element, and first and second reference voltage couplings on the conductive antenna element. In addition, an electrical distance between the feed coupling and either of the first and second reference voltage couplings may be greater than an electrical distance between the first and second reference voltage couplings.

More particularly, the planar inverted F antenna may be configured for operation at an operating frequency band, and a current null may be present on the conductive antenna element between the feed coupling and at least one of the reference voltage couplings at the operating frequency band. The operating frequency band, for example, can be in the range of approximately 1700 MHz to 2500 MHz. Moreover, the operating frequency band may include a high-frequency band, the planar inverted F antenna may be further configured for operation at a low-frequency

band, and the current null may be present at the high-frequency band but not at the low-frequency band.

In addition, a printed circuit board may include a reference voltage conductor and an antenna feed conductor, the first and second reference voltage couplings may be electrically coupled to the reference voltage conductor of the printed circuit board, and the feed coupling may be electrically coupled to the antenna feed conductor. Moreover, at least one of the first and second reference voltage couplings may be electrically coupled to the reference voltage conductor through an electrical short or through a non-zero impedance. The feed coupling and at least one of the first and second reference voltage couplings may be separated by an electrical distance of at least approximately 15 mm, and/or the feed coupling may be spaced apart from at least one of the first and second reference voltage couplings by an electrical distance of at least approximately 10 mm.

In a particular embodiment, the conductive antenna element may include first, second, and third antenna segments. The first and second antenna segments may be spaced apart, and the third antenna segment may be coupled between the first and second antenna segments. Moreover, the feed coupling and the first and second reference voltage couplings may be on the first segment with the feed coupling being between the first and second reference voltage couplings. The conductive antenna element may further include a fourth antenna segment coupled to the first antenna segment, and the fourth antenna segment may be coupled to the first antenna segment adjacent the feed coupling.

In other embodiments, the antenna element may include an antenna base and first and second antenna segments. The feed coupling and the first and second reference voltage couplings may be provided on the antenna base. The first segment may extending from the antenna base adjacent the first reference voltage coupling, and the second antenna segment may extend from the antenna base adjacent the feed coupling.

According to still additional embodiments of the present invention, a communications device may include a transceiver and a planar inverted F antenna. The transceiver may be configured to transmit and/or receive radio communications at an operating frequency band, and the transceiver may provide a reference voltage and a transceiver feed. The planar inverted F antenna may be configured for operation at the operating frequency band, and the planar inverted F antenna may include first and

second antenna segments wherein the first and second antenna segments are separated by at least approximately 3 mm. A third antenna segment may couple the first and second antenna segments, and reference voltage and feed couplings may be provided on the first antenna segment. The reference voltage coupling of the planar inverted F antenna may be coupled to the reference voltage of the transceiver, the feed coupling may be coupled to the transceiver feed, and a current null may be present between the feed and reference voltage couplings at the operating frequency band.

According to yet additional embodiments of the present invention, a communications device may include a transceiver and a planar inverted F antenna. The transceiver may be configured to transmit and/or receive radio communications at an operating frequency band, and the transceiver may provide a reference voltage and a transceiver feed. The planar inverted F antenna may include a conductive antenna element and a feed coupling on the conductive antenna element wherein the feed coupling is coupled to the transceiver feed. The antenna may also include first and second reference voltage couplings on the conductive antenna element wherein the first and second reference voltage couplings are coupled to the reference voltage of the transceiver. In addition, an electrical distance between the feed coupling and either of the first and second reference voltage couplings may be greater than an electrical distance between the first and second reference voltage couplings.

BRIEF DESCRIPTION OF THE DRAWIGNS

Figures 1a-c are plan, top, and side views of a planar inverted F antenna (PIFA) according to first embodiments of the present invention.

Figures 2a-c are plan, top, and side views of a planar inverted F antenna (PIFA) according to second embodiments of the present invention.

Figures 3a-c are plan, top, and side views of a planar inverted F antenna (PIFA) according to third embodiments of the present invention.

Figures 4a and 4b are side and plan views of a dual-band planar inverted F antenna (PIFA), and Figure 4c is a corresponding graph of a voltage standing wave radio (VSWR) response for the planar inverted F antenna of Figures 4a-b.

Figure 5a is a plan view of a planar inverted F antenna (PIFA) according to additional embodiments of the present invention having dimensions of approximately 51.7 mm X 36.5 mm X 7 mm.

Figures 5b is a graph illustrating simulated voltage standing wave ratio (VSWR) response of the planar inverted F antenna of Figure 5a without a user finger and with markers at 824 MHz, 894 MHz, 1850 MHz, and 2700 MHz.

Figures 5c is a graph illustrating simulated voltage standing wave ratio (VSWR) response of the planar inverted F antenna of Figure 5a with a user finger proximate to the antenna and with markers at 824 MHz, 894 MHz, 1850 MHz, and 2700 MHz.

Figures 5d and 5e are simulated current patterns for the planar inverted F antenna of Figure 5a at 2GHz.

Figures 5f and 5g illustrate low-frequency (1 GHz) and high-frequency (2.5GHz) band current densities (time averaged) for planar inverted F antennas according to embodiments of the present invention.

Figure 6a is a plan view of a planar inverted F antenna (PIFA) according to still additional embodiments of the present invention.

Figure 6b is a graph illustrating simulated voltage standing wave ratio (VSWR) responses of the planar inverted F antenna of Figure 6a with markers at 824 MHz, 894 MHz, 1710 MHz, and 1990 MHz.

Figures 6c-6g are simulated current patterns of the PIFA antenna of Figure 6a at 1GHz, 2.2GHz, 2.4GHz, 2.6GHz, and 2.7GHz, respectively.

Figure 7a is a plan view of a planar inverted F antenna (PIFA) according to yet additional embodiments of the present invention.

Figure 7b is a perspective view of the planar inverted F antenna (PIFA) of Figure 7a including simulated current densities at 1.7GHz.

Figure 7c is a graph illustrating simulated voltage standing wave ratio (VSWR) responses of the planar inverted F antenna (PIFA) of Figures 7a-b without a user finger and with low-frequency band markers at 824 MHz and 960 MHz and with high-frequency band markers at 1710 MHz and 1990 MHz.

Figure 7d is a graph illustrating simulated voltage standing wave ratio (VSWR) responses of the planar inverted F antenna (PIFA) of Figures 7a-b with a user finger proximate to the antenna and with low-frequency band markers at 824 MHz and 960 MHz and with high-frequency band markers at 1710 MHz and 1990 MHz.

Figure 8a is a plan view of a planar inverted F antenna (PIFA) according to more embodiments of the present invention.

Figure 8b is a perspective view of the planar inverted F antenna (PIFA) of Figure 8a including simulated current densities at 1.8GHz.

Figure 8c is a graph illustrating simulated voltage standing wave ratio (VSWR) responses of the planar inverted F antenna (PIFA) of Figures 8a-b without a user finger and with low-frequency band markers at 824 MHz and 960 MHz and with high-frequency band markers at 1710 MHz and 2350 MHz.

Figure 8d is a graph illustrating simulated voltage standing wave ratio (VSWR) responses of the planar inverted F antenna (PIFA) of Figures 8a-b with a user finger proximate to the antenna and with low-frequency band markers at 824 MHz and 960 MHz and with high-frequency band markers at 1710 MHz and 2350 MHz.

Figure 9 illustrates one example of a prior art PIFA (planar inverted "F" antenna).

DETAILED DESCRIPTION

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown. The invention may, however, be embodied in different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. In the drawings, the dimensions of various elements may be exaggerated for clarity. It will also be understood that when an element is referred to as being "coupled" or "connected" to another element, it can be directly coupled or connected to the other element, or intervening elements may also be present. Similarly, when an element is referred to as being "on" another element, it can be directly on the other element, or intervening elements may also be present. Like numbers refer to like elements throughout. This disclosure also uses relative terms, such as "side", "front", "back", "top", and/or "bottom" to describe some of the elements in the embodiments. These relative terms are used for the sake of convenience and clarity when referring to the drawings, but are not to be construed to mean that the elements so described can only be positioned relative to one another as shown.

A planar inverted F antenna according to embodiments of the present invention is illustrated in Figures 1a-c. As shown, the planar inverted F antenna **101**

may include a first antenna segment **103**, a second antenna segment **105**, a third antenna segment **107**, a reference voltage coupling **108**, and a feed coupling **109**. More particularly, the first and second antenna segments **103** and **105** are separated by at least approximately 3 mm, and the third antenna segment **107** is coupled between the first and second antenna segments **103** and **105**. Moreover, the reference voltage coupling **108** and the feed coupling **109** are on the first antenna segment **103**. In addition, the planar inverted F antenna **101** may be configured for operation at one or more operating frequency bands, and a current null may be present between the reference voltage and feed couplings **108** and **109** at an operating frequency band. More particularly, the reference voltage and feed couplings **108** and **109** on the PIFA antenna **101** may be separated by at least approximately 15 mm.

According to particular embodiments of the present invention, the first antenna segment **103** may be 40 mm long and 7 mm wide, the second antenna segment **105** may be 50 mm long and 7 mm wide, and the first and second antenna segments **103** and **105** may be separated by 26 mm. Moreover, the third antenna segment **107** may be 26 mm long between the first and second antenna segments **103** and **105**, and the third antenna segment may be 15 mm wide.

As further shown in Figures 1a-c, the planar inverted F antenna **101** may be coupled to a printed circuit board **111** through the reference voltage and feed couplings **108** and **109**. More particularly, a transceiver **115** may be provided as one or a plurality of integrated and/or discrete electronic devices on the printed circuit board **111**. The transceiver **115** may be configured to transmit and/or receive radio communications at the operating frequency band(s), and the transceiver may provide a reference voltage and a transceiver feed. Conductive portions of the printed circuit board **111** provide an electrical coupling between the reference voltage coupling **108** of the planar inverted F antenna and the reference voltage of the transceiver **115**.

More particularly, a conductive layer within the printed circuit board **111** may provide a reference voltage conductor (such as a ground plane), and the reference voltage coupling **108** of the planar inverted F antenna and the reference voltage of the transceiver may both be coupled to the reference voltage conductor of the printed circuit board **111**. Additional conductive portions of the printed circuit board **111** may provide a feed conductor between the feed coupling **109** of the planar inverted F antenna and the transceiver feed. While the transceiver **115** is illustrated on the printed circuit board **111**, portions or all of the transceiver **115** may be located remote

from the printed circuit board **111** (such as on other printed circuit boards) and electrically coupled to the printed circuit board **111**. Moreover, additional electronic devices (other than the transceiver **115**) may be provided on the printed circuit board **111**.

In addition, the reference voltage coupling **108** of the PIFA antenna **101** can be electrically coupled to the reference voltage conductor of the printed circuit board **111** through an electrical short. In an alternative embodiment, the reference voltage coupling **108** of the PIFA antenna **101** may be electrically coupled to the reference voltage conductor of the printed circuit board **111** through a non-zero impedance element such as a capacitance, inductance, and/or resistance. For example, an impedance element can be provided as a discrete impedance element(s) soldered to the printed circuit board and electrically connected between the reference voltage coupling **108** of the PIFA antenna **101** and the reference voltage conductor of the printed circuit board **111**. Accordingly, one or more impedance elements can be used to tune the PIFA antenna **101**.

In an alternative embodiment, a geometry of the reference voltage coupling **108** and/or a conductive layer on the printed circuit board may provide an impedance element. In yet another alternative embodiment, an impedance element may be provided between the reference voltage conductor of the printed circuit board and the reference voltage of the transceiver **115**. In addition or in an alternative, the PIFA antenna **101** may be tuned by providing an impedance element(s) between the feed coupling **109** of the PIFA antenna **101** and the transceiver feed.

As shown in Figures 1a-c, the first and second antenna segments **103** and **105** may be rectilinear and parallel. Moreover, the third antenna segment **107** is coupled to the first and second antenna segments **103** and **105** at ends of the first and second antenna segments. In addition, the feed coupling **109** is spaced apart from the third antenna segment **107** by a greater distance than the reference voltage coupling **108**, and the first and the third antenna segments **103** and **105** define an angle of approximately 90 degrees. The first antenna segment **103** may also be longer than the second antenna segment **105**.

For example, an operating frequency band of the PIFA antenna **201** may be in the range of approximately 1700 MHz to 2500 MHz. Moreover, the planar inverted F antenna **101** may be configured for communications operation at a high-frequency band and at a low-frequency band, and the current null may be present between the

reference voltage and feed couplings **108** and **109** during communications operations at the high-frequency band. The current null, however, may not be present between the reference voltage and feed couplings **108** and **109** during communications operations at the low-frequency band. By way of example, the PIFA antenna **103** may be used in a mobile terminal providing wireless communications at a low-frequency band(s), such as a cell band (approximately 824 MHz to approximately 894 MHz), and providing wireless communications at a high-frequency band(s), such as a Personal Communications Services PCS band (approximately 1850 MHz to approximately 1990 MHz), a Universal Mobile Telecommunications System UMTS band (including frequencies from approximately 1900 MHz to approximately 2200 MHz), and/or a Bluetooth band (approximately 2400 MHz to approximately 2485 MHz). As discussed above, the current null may be present when communicating in the high-frequency PCS, UMTS, and/or Bluetooth bands, but not when communicating in the low-frequency cell band.

While only a single reference voltage coupling **108** is illustrated in Figures 1a-c, it will be understood that additional reference voltage couplings may be provided according to embodiments of the present invention. For example, a second reference voltage coupling may be provided on the first antenna segment **103** such that the feed coupling **109** is between the first and second reference voltage couplings. Moreover, an impedance element(s) (such as a capacitor, inductor, and/or resistor) and/or a switch(s) may be included in series between the reference voltage conductor of the printed circuit board **111** and one or both of the reference voltage couplings of the PIFA antenna. Additional antenna segments may also be included on the PIFA antenna of Figures 1a-c. For example, a fourth antenna segment may extend from the first antenna segment **103** adjacent the feed coupling **109** toward the second antenna segment **105**.

A planar inverted F antenna (PIFA) according to additional embodiments of the present invention is illustrated in Figures 2a-c. As shown in Figures 2a-c, the planar inverted F antenna **201** may include a feed coupling **209**, and first and second reference voltage couplings **208** and **210**. More particularly, an electrical distance between the feed coupling **209** and either of the first and second reference voltage couplings **208** and **210** is greater than an electrical distance between the first and second reference voltage couplings **208** and **210**. As used herein, the term electrical distance refers to the shortest path of electrical current between two points.

Moreover, the planar inverted F antenna **201** may be configured for operation at one or more operating frequency bands such that a current null is present on the planar inverted F antenna **201** between the feed coupling **209** and at least one of the reference voltage couplings **208** and **210** at an operating frequency band. According to particular embodiments of the present invention, current nulls may be present on the PIFA antenna between the feed coupling **209** and both of the reference voltage couplings **208** and **210**.

As further shown in Figures 2a-c, the PIFA antenna **201** may include first, second, and third antenna segments **203**, **205**, and **207**, with the first and second antenna segments being spaced apart and with the third antenna segment being coupled between the first and second antenna segments. Moreover, the feed coupling **209** and the first and second reference voltage couplings **208** and **210** may be provided on the first antenna segment **203**. The PIFA antenna **201** may also include a fourth antenna segment **221** extending from the first antenna segment **203** adjacent the feed coupling **209** toward the second antenna segment **205**.

According to particular embodiments of the present invention, the first antenna segment **203** may be 40 mm long and 7 mm wide, the second antenna segment **205** may be 50 mm long and 7 mm wide, and the first and second antenna segments **203** and **205** may be separated by 26 mm. Moreover, the third antenna segment **207** may be 26 mm long between the first and second antenna segments **203** and **205**, and the third antenna segment may be 15 mm wide. In addition, the fourth antenna segment **221** may be 15 mm long and 7 mm wide.

As further shown in Figures 2a-c, the planar inverted F antenna **201** may be coupled to a printed circuit board **211** through the reference voltage couplings **208** and **210** and the feed coupling **209**. More particularly, a transceiver **215** may be provided as one or a plurality of integrated and/or discrete electronic devices on the printed circuit board **211**. The transceiver **215** may be configured to transmit and/or receive radio communications at the operating frequency band(s), and the transceiver may provide a reference voltage and a transceiver feed. Conductive portions of the printed circuit board **211** provide an electrical coupling between the reference voltage couplings **208** and **210** of the planar inverted F antenna and the reference voltage of the transceiver **215**.

More particularly, a conductive layer within the printed circuit board **211** may provide a reference voltage conductor (such as a ground plane), and the reference

voltage coupling **208** of the planar inverted F antenna and the reference voltage of the transceiver may both be coupled to the reference voltage conductor of the printed circuit board **211**. Additional conductive portions of the printed circuit board **211** may provide a feed conductor between the feed coupling **209** of the planar inverted F antenna and the transceiver feed. While the transceiver **215** is illustrated on the printed circuit board **211**, portions or all of the transceiver **215** may be located remote from the printed circuit board **211** (such as on other printed circuit boards) and electrically coupled to the printed circuit board **211**. Moreover, additional electronic devices (other than the transceiver **215**) may be provided on the printed circuit board **211**.

In addition, each of the reference voltage couplings **208** and **210** of the PIFA antenna **201** can be electrically coupled to the reference voltage conductor of the printed circuit board **211** through an electrical short. In an alternative, one or both of the reference voltage couplings **208** and **210** of the PIFA antenna **201** may be electrically coupled to the reference voltage conductor of the printed circuit board **211** through an impedance element such as a capacitance, inductance, and/or resistance. For example, an impedance element(s) can be provided as a discrete impedance element(s) soldered to the printed circuit board and electrically connected between one or both of the reference voltage couplings **208** and **210** of the PIFA antenna **201** and the reference voltage conductor of the printed circuit board **211**. Accordingly, one or more impedance elements can be used to tune the PIFA antenna **201**.

In an alternative embodiment, a geometry of one or both of the reference voltage couplings **208** and **210** and/or a conductive layer on the printed circuit board may provide an impedance element. In yet another alternative embodiment, an impedance element may be provided between the reference voltage conductor of the printed circuit board and the reference voltage of the transceiver **215**. In addition or in an alternative, the PIFA antenna **201** may be tuned by providing an impedance element(s) between the feed coupling **209** of the PIFA antenna **201** and the transceiver feed.

For example, an operating frequency band of the PIFA antenna **201** may be in the range of approximately 1700 MHz to 2500 MHz. Moreover, the planar inverted F antenna **201** may be configured for communications operation at a high-frequency band and at a low-frequency band, and the current null may be present between the feed coupling **209** and each of the reference voltage couplings **208** and **210** during

communications operations at the high-frequency band. The current null, however, may not be present between the feed coupling **209** and either of the reference voltage couplings **208** and **210** during communications operations at the low-frequency band. By way of example, the PIFA antenna **201** may be used in a mobile terminal providing wireless communications at a low-frequency band(s), such as a cell band (approximately 824 MHz to approximately 894 MHz), and providing wireless communications at a high-frequency band(s), such as a Personal Communications Services PCS band (approximately 1850 MHz to approximately 1990 MHz), a Universal Mobile Telecommunications System UMTS band (including frequencies from approximately 1900 MHz to approximately 2200 MHz) and/or a Bluetooth band (approximately 2400 MHz to approximately 2485 MHz). As discussed above, the current null may be present when communicating in one or more of the high-frequency PCS, UMTS, and/or Bluetooth bands, but not when communicating in the low-frequency cell band.

Moreover, the the feed coupling **209** and at least one of the first and second reference voltage couplings **208** and **210** may be separated by an electrical distance of at least approximately 15 mm. In addition, the feed coupling **209** may be spaced apart from each of the first and second reference voltage couplings by an electrical distance of at least approximately 8 mm.

A planar inverted F antenna ("PIFA") according to yet additional embodiments of the present invention is illustrated in Figures 3a-c. As shown in Figures 3a-c, the PIFA antenna **301** may include a feed coupling **309**, and first and second reference voltage couplings **308** and **310**. More particularly, an electrical distance between the feed coupling **309** and either of the first and second reference voltage couplings **308** and **310** is less than an electrical distance between the first and second reference voltage couplings **308** and **310**. Moreover, the planar inverted F antenna **301** may be configured for operation at an operating frequency band such that a current null is present on the PIFA antenna between the feed coupling **309** and at least one of the reference voltage couplings **308** and **310** at at least one of the operating frequency bands. According to particular embodiments of the present invention, current nulls may be present on the PIFA antenna between the feed coupling **309** and one or both of the reference voltage couplings **308** and **310**.

As further shown in Figures 3a-c, the PIFA antenna **301** may include an antenna base **303**; a first rectilinear segment **305** extending from the antenna base **303**

adjacent the reference voltage coupling **308**; and a second rectilinear segment **307** extending from the antenna base **303** adjacent the feed coupling **309**. More particularly, the antenna base **303** may be rectangular in shape with the feed coupling **309** and the first and second reference voltage couplings **308** and **310** being provided at different corners thereof. While the antenna base **303** is illustrated as having an opening **304** therein, the opening may not be required. As shown, the first rectilinear antenna segment **305** may be coupled to the antenna base **303** adjacent the reference voltage coupling **308**, and the second rectilinear antenna segment **307** may be coupled to the antenna base **303** adjacent the feed coupling **309**. Moreover, the first antenna segment **305** may be short relative to the second antenna segment **307**.

According to particular embodiments of the present invention, the antenna base **303** may be 35 mm long (from the reference voltage coupling **308** to the feed coupling **309**) and 8 mm wide (from the feed coupling **309** to the reference voltage coupling **310**). The antenna segment **305** may be 16 mm long and 2 mm wide, and the antenna segment **307** may be 55 mm long and 2 mm wide. The first and second antenna segments **305** and **307** may be separated by 32 mm.

As further shown in Figures 3a-c, the planar inverted F antenna **301** may be coupled to a printed circuit board **311** through the reference voltage couplings **308** and **310** and the feed coupling **309**. More particularly, a transceiver **315** may be provided as one or a plurality of integrated and/or discrete electronic devices on the printed circuit board **311**. The transceiver **315** may be configured to transmit and/or receive radio communications at the operating frequency band(s), and the transceiver may provide a reference voltage and a transceiver feed. Conductive portions of the printed circuit board **311** provide an electrical coupling between the reference voltage couplings **308** and **310** of the planar inverted F antenna and the reference voltage of the transceiver **315**.

More particularly, a conductive layer within the printed circuit board **311** may provide a reference voltage conductor (such as a ground plane), and the reference voltage coupling **308** of the planar inverted F antenna and the reference voltage of the transceiver may both be coupled to the reference voltage conductor of the printed circuit board **311**. Additional conductive portions of the printed circuit board **311** may provide a feed conductor between the feed coupling **309** of the planar inverted F antenna and the transceiver feed. While the transceiver **315** is illustrated on the printed circuit board **311**, portions or all of the transceiver **315** may be located remote

from the printed circuit board **311** (such as on other printed circuit boards) and electrically coupled to the printed circuit board **311**. Moreover, additional electronic devices (other than the transceiver **315**) may be provided on the printed circuit board **311**.

In addition, each of the reference voltage couplings **308** and **310** of the PIFA antenna **301** can be electrically coupled to the reference voltage conductor of the printed circuit board **311** through an electrical short. In an alternative embodiment, one or both of the reference voltage couplings **308** and **310** of the PIFA antenna **301** may be electrically coupled to the reference voltage conductor of the printed circuit board **311** through an impedance element such as a capacitance, inductance, and/or resistance. For example, an impedance element(s) can be provided as a discrete impedance element(s) soldered to the printed circuit board and electrically connected between one or both of the reference voltage couplings **308** and **310** of the PIFA antenna **301** and the reference voltage conductor of the printed circuit board **311**. Accordingly, one or more impedance elements can be used to tune the PIFA antenna **301**.

In an alternative embodiment, a geometry of one or both of the reference voltage couplings **308** and **310** and/or a conductive layer on the printed circuit board may provide an impedance element. In yet another alternative embodiment, an impedance element may be provided between the reference voltage conductor of the printed circuit board and the reference voltage of the transceiver **315**. In addition or in an alternative, the PIFA antenna **301** may be tuned by providing an impedance element(s) between the feed coupling **309** of the PIFA antenna **301** and the transceiver feed. For example, reference voltage coupling **310** may be capacitively coupled to the reference voltage conductor of the printed circuit board to increase bandwidth at high band operating frequencies.

For example, an operating frequency band of the PIFA antenna **301** may be in the range of approximately 1700 MHz to 2500MHs. Moreover, the planar inverted F antenna **301** may be configured for communications operation at a high-frequency band and at a low-frequency band, and the current null may be present between the feed coupling **309** and one or more of the reference voltage couplings **308** and **310** during communications operations at the high-frequency band. According to some embodiments, the current null may be present between the feed coupling **309** and the reference voltage coupling **308** (but not between the feed coupling **309** and the

reference voltage coupling **310**) during communications at the high-frequency band. The current null, however, may not be present between the feed coupling **309** and either of the reference voltage couplings **308** and **310** during communications operations at the low-frequency band. By way of example, the PIFA antenna **301** may be used in a mobile terminal providing wireless communications at a low-frequency band(s), such as a cell band (approximately 824 MHz to approximately 894 MHz), and providing wireless communications at a high-frequency band(s), such as a Personal Communications Services PCS band (approximately 1850 MHz to approximately 1990 MHz), a Universal Mobile Telecommunications System UMTS band (including frequencies from approximately 1900 MHz to approximately 2200 MHz), and/or a Bluetooth band (approximately 2400 MHz to approximately 2485 MHz). As discussed above, the current null may be present when communicating in one or more of the high-frequency PCS, UMTS, and/or Bluetooth bands, but not when communicating in the low-frequency cell band.

Moreover, the feed coupling **309** and at least one of the first and second reference voltage couplings **308** and **310** may be separated by an electrical distance of at least approximately 15 mm. In addition, the feed coupling **309** may be spaced apart from the first reference voltage coupling **308** by an electrical distance of at least approximately 10 mm.

A multi-band monopole antenna may require significant separation from a ground plane of the communication device. A planar inverted F antenna (PIFA) structure may have approximately 10% to 15% bandwidth at high-frequency bands (i.e. greater than approximately 1700 MHz). A PIFA antenna may provide advantages that a PIFA antenna can be internal to the body of the phone and/or that radiation from a PIFA antenna can be substantially directed away from the user when being held to the user's ear.

A PIFA antenna structure with separated feed and ground couplings may provide an advantage that peak currents on the printed circuit board (PCB) can be spread and the resulting peak radiation levels can be reduced. Many PIFA antennas in use today have separation of feed and ground couplings on the order of 2-8 mm. Desirable characteristics of an antenna for a mobile telephone may include: internal to the housing of the mobile telephone which may reduce breakage and/or lower cost; small in size thereby allowing for small overall phone size; high in efficiency and/or gain; directional away from the user when in use; not easily de-tuned by the user

placing his/her finger/hand over the antenna; and predominantly vertically polarized when the mobile telephone is in the upright position.

In many internal PIFA antennas, the antenna feed coupling may be placed next to the ground coupling with a spacing of approximately 3 mm to 6 mm therebetween. Such a PIFA antenna may be relatively directional and may provide relatively high gain. With a 3 mm to 6 mm spacing, however, the antenna may be detuned relatively easily such as when a finger/hand is placed on the housing of the mobile telephone over the antenna. When detuned, a Voltage Standing Wave Ratio (VSWR) response mismatch may cause a multiple dB decrease in gain in addition to absorption loss by the user's finger/hand. Mobile telephones (such as Nokia models 3210 and 7210) may spread the feed and ground couplings further than 6 mm and may thereby obtain higher gain, a more directional pattern away from the user, and/or reduced sensitivity to detuning. In addition, coupling may be used to excite the low-band branch to resonate at high-band frequencies.

Many PIFA antennas may act as ¼-wave radiators at both low and high-frequency bands. As shown in Figures 4a-c, these antennas may include a branched radiating element **401** that has an RF feed **403** with a ground coupling **405** that is placed in close proximity near one end of the radiating element **401**. The PIFA antenna of Figures 4a-c may also include a low-band branch **407** and a high-band branch **409**.

A PIFA antenna may act as a ¼-wave resonator at low-band and may have a high-band radiating structure that resembles the performance of a ½-wave radiator. A ½-wave performance may provide better gain and less performance degradation due to the presence of a user than a ¼-wave antenna.

When the high-band branch **409** of PIFA antenna **401** is lengthened to ½-wave (or longer), an impedance match may be degraded and the antenna may no longer be functional at relatively high-band frequencies (i.e. greater than 1700 MHz). High-band performance may be improved by fixing the ground coupling at the intersection of the two branches and separating the RF connection along the other antenna branch. As a result, the branch with the RF feed may provide a distributed impedance match to the high-band element. Two matching components (such as a series capacitor and shunt inductor or a series inductor and shunt capacitance) may be used to match to a high impedance antenna. By moving the RF feed, the matching components may not

be needed. In addition, by controlling dimensions of the branch and location of the feed, additional bandwidth may be achievable.

According to embodiments of the present invention, a PIFA antenna may include at least two branches, and the radiating structure of the branch (or combination of branches) may be ½- wavelength (or longer) at some frequencies of operation. With orthogonal or widely separated branches, the coupling between the branches can be reduced. In addition, a ground coupling may be located at (or near) a junction of two branches, and this location of the ground coupling may establish a point of low-impedance and high radiating current at the junction between the branches. An RF feed coupling may be located away from the ground coupling along the other antenna branch. This displacement of feed and ground couplings may allow for better control of an impedance match of the PIFA antenna. For example, with the feed coupling located away from the far edge of the branch, additional bandwidth can be achieved. A portion of the branch that extends beyond the feed coupling may provide additional matching that can readily be tuned by controlling an area and/or length of the element.

According to additional embodiments of the present invention, the feed and ground couplings may be separated by a significant distance. In some PIFA antenna designs for the 1-2 GHz frequencies, spacing may be between 2 and 7 mm. In PIFA antennas according to some embodiments of the present invention, spacing between feed and ground couplings may be between about 20 mm and 40 mm or greater. The additional spacing according to some embodiments of the present invention may allow for creation of a current null at high-band frequencies, and may allow for additional bandwidth as the current flow of both the feed and ground couplings may be less than 90 degrees out of phase through a relatively large bandwidth (i.e. with current flowing up from the ground as it is flowing in from the feed). In some of the embodiments, a branch may be coupled between the feed and ground couplings to allow additional bandwidth to be achieved.

According to embodiments of the present invention, "detuning" resulting from placement of the user's finger over the PIFA antenna may bring the antenna closer to 50 Ohms, and may result in a Voltage Standing Wave Ratio (VSWR) response of better than 2:1 across multiple frequency 4 bands (i.e. the cell band at approximately 824 MHz to approximately 894 MHz; the PCS band at approximately 1850 MHz to approximately 1990 MHz; the UMTS band including frequencies from approximately

1900 MHz to approximately 2200 MHz; and/or the Bluetooth band at approximately 2400 MHz to approximately 2485 MHz), largely independent of where the finger is placed for the high-band(s).

In additional embodiments of the present invention (such as illustrated in Figures 7a-b, for example), radiation toward a user can be reduced (4-6 dB lower than away from the user). In other embodiments (such as illustrated in Figures 8a-b, for example), gain may be more omni-directional. With separated feed and ground couplings, peak currents can be distributed over a greater area, thereby improving performance when placed near a user's head in an application such as a mobile radiotelephone. In still additional embodiments (such as illustrated in Figures 8a-b, for example), PIFA antenna elements can be shaped such that they can be located adjacent to a battery pack, etc., making a size reserved for the antenna similar to that of other products.

A multi-band PIFA antenna **501** according to embodiments of the present invention is illustrated in Figure 5a, and simulated VSWR response and current distributions for the antenna of Figure 5a are illustrated in Figures 5b and 5c, respectively. According to particular embodiments of the present invention, the PIFA antenna of Figure 5a may have dimensions of approximately 51.7 mm by 36.5 mm by 7 mm. Moreover, the antenna **501** of Figure 5a may include first segment **507** and second segment **509** with a third segment **511** therebetween. Moreover, the ground coupling **503** may be located adjacent the intersection of the first and third segments **507** and **511**, and the ground coupling **503** may be centered relative to a width of the third segment **511**. By fixing the ground coupling **503** adjacent the perpendicular intersection of the first segment **507** and the third segment **511** and by fixing the feed coupling on the first segment **507** as shown, significant separation of the feed and ground couplings may be provided without significantly impacting bandwidth and/or gain at low-frequency bands. The ground coupling **503** may be coupled to ground plane **515**, and the ground plane **515** may extend further than illustrated in Figure 5a.

The graphs of Figures 5b and 5c illustrate simulated Voltage Standing Wave Ratio (VSWR) responses for the PIFA antenna **501** of Figure 5a with the PIFA antenna **501** separated from a printed circuit board by approximately 7 mm. Figure 5b illustrates VSWR responses without the presence of a user's finger, and Figure 5c illustrates VSWR responses with a user's finger on the PIFA antenna **501**. Moreover,

markers are placed on the graphs of Figures 5b and 5c at 824 MHz, 894 MHz, 1850 MHz, and 2700 MHz.

As seen in Figure 5b, the sample structure may have a VSWR response of less than 5:1 for the cell band (824-894 MHz), and the sample structure may have a VSWR response of less than 4:1 for 1850-2700 MHz (which may include PCS, WCDMA, Bluetooth, and/or additional bandwidths). In addition, with user finger loading (which may be common when the user holds the phone), a VSWR response may be better than 2.5:1 for high-band frequencies (i.e. for frequencies greater than 1700 MHz). As a result, mismatch losses on the antenna may be less than 0.9 dB. This result may be similar to that of antennas covering only a single high-frequency band (for example, 1850 MHz to 1990 MHz providing approximately 7% bandwidth). Furthermore, currently used antennas for cell-phone applications may detune relatively easily when the user's finger is placed on the antenna, resulting in VSWR responses of 6:1 or greater. By using physically long high-band resonators in the PIFA antenna structure of Figure 5a, detuning may be reduced and a VSWR response may be maintained below 3:1 for most of a high-frequency band. Accordingly, mismatch losses may be improved by as much as 2.5 dB or more over current designs.

As shown in Figure 5c, there may be a current null between the ground and feed couplings **503** and **505**. Because of this null and a resonance created on the low-band branch, a bandwidth at high-band of greater than 30% can be possible. Typical patch antennas and PIFA antennas may have a bandwidth of around 10% for a VSWR response of 4:1 or lower. Furthermore, by selectively removing the ground plane, even greater bandwidths can be achieved.

PIFA antennas according to embodiments of the present invention may be suitable, for example, for multi-band clamshell radiotelephones. More particularly, PIFA antennas according to embodiments of the present invention may be adapted for use for both low-frequency band(s) communications (for example, cellular band at approximately 824 MHz to approximately 894 MHz) and high-frequency band(s) communications (for example, PCS band at approximately 1850 MHz to approximately 1990 MHz, UMTS band including frequencies from approximately 1900 MHz to approximately 2200 MHz, and/or Bluetooth band at approximately 2400 MHz to approximately 2485 MHz). Moreover, by removing some of the ground plane near the top of the phone, the antenna of Figure 5a can also be made to operate in other bands, including DCS (approximately 1710 MHz to approximately 1850

MHz). Other embodiments of the present invention may also be tuned to cover all of these bands as well. Figures 5d and 5e illustrate simulated current patterns for the PIFA antenna of Figure 5a at 2GHz.

Figures 5f and 5g illustrate simulated current densities for a PIFA structure similar to that of Figure 5a. As shown in Figures 5f and 5g, a PIFA antenna structure according to embodiments of the present invention may include a first antenna segment **507'**, a second antenna segment **509'**, a ground coupling **503'**, a feed coupling **505'**, and a third antenna segment **511'** between the first and second antenna segments **507'** and **509'**. As shown in Figures 5f and 5g, the third antenna segment **511'** may include an opening therein. The ground coupling **503'** may be coupled to ground plane **515'**. Simulated current densities for the PIFA antenna structure at 1GHz are illustrated in Figure 5f, and simulated current densities for the PIFA antenna structure at 2.5GHz are illustrated in Figure 5g. The ground plane **515'** may extend further than illustrated in Figures 5f and 5g.

In alternative embodiments of the present invention illustrated in Figure 6a, a PIFA antenna may include a first antenna segment **607**, a second antenna segment **609**, a third antenna segment **611**, first ground coupling **603a**, second ground coupling **603b**, and feed coupling **605**. Moreover, the first and second antenna segments **607** and **609** may be coupled though a fourth antenna segment **615**, and the feed coupling **605** may be provided on the first antenna segment **607** between the first and second ground couplings **603a-b**. Moreover, the third antenna segment **611** may be provided adjacent to the feed coupling **605** with the feed coupling centered relative to a width of the third antenna element **611**. Moreover, the fourth antenna segment **615** may have an opening therein. The first and second ground couplings **603a-b** may be coupled to ground plane **621**. As shown in Figure 6b, a resulting low-frequency band resonance of the PIFA antenna of Figure 6a may be narrower and deeper than that of the PIFA antenna illustrated in Figure 5a. In addition, a DCS/PCS resonance of the PIFA antenna of Figure 6a may be narrower and deeper than that of the PIFA antenna of Figure 5a.

Simulated current densities are illustrated in Figures 6c-g for the PIFA antenna of Figure 6a. Figure 6c illustrates simulated current densities at 1GHz, Figure 6d illustrates simulated current densities at 2.2GHz, Figure 6e illustrates simulated current densities at 2.4GHz, Figure 6f illustrates simulated current densities at

2.6GHz, and Figure 6g illustrates simulated current densities at 2.7GHz. The ground plane **621** illustrated in Figures 6a and 6c-g may extend further than illustrated.

According to additional embodiments of the present invention, the PIFA antenna of Figures 7a-b, a PIFA antenna may include first through fourth antenna segments **701**, **703**, **704**, **705**, and **707**. The PIFA antenna of Figures 7a-b may also include a feed coupling **709** and ground couplings **711a-b** to the printed circuit board **717**. The PIFA antenna of Figures 7a-b is approximately 39 mm wide and 55 mm tall, and it is modeled as being 10 mm from the ground plane of the printed circuit board **717**. Moreover, Figure 7b provides simulated current densities at 1.7GHz.

The graph of Figure 7c illustrates simulated voltage standing wave ratio (VSWR) responses for the PIFA antenna of Figures 7a-b without the presence of a user's finger. The graph of Figure 7d illustrates simulated voltage standing wave ratio (VSWR) responses for the PIFA antenna of Figures 7a-b with a user's finger adjacent the antenna. Low-band frequency markers are provided at 824 MHz and 960 MHz. High-frequency band markers are provided at 1710 MHz and 1990 MHz.

Additional embodiments of the present invention are illustrated in Figures 8a-d. As shown in Figures 8a-b, a PIFA antenna **801** may include an antenna base **803**, and first and second antenna segments **805** and **807**. Moreover, the antenna base **803** may be rectangular with an opening therein, a feed coupling **809** may be located at a corner of the antenna base **803** adjacent the antenna segment **805**, and a first ground coupling **811** may be located at a corner of the antenna base **803** adjacent the antenna segment **807**. Moreover, a second ground coupling **815** may be located at a corner of the antenna base **803** opposite the first ground coupling **811**.

The antenna base **803** between the feed and ground couplings **809** and **811** may be relatively wide, but widths of the antenna segments **805** and **807** extending off of the feed and ground couplings **809** and **811** may be relatively narrow. As before, ground coupling **815** to the ground plane of the printed circuit board **821** can be used to obtain additional bandwidth. In physical models, wires with a diameter of about 0.8 mm can be used for the antenna segments **805** and **807** extending from the antenna base **803**. According to particular embodiments, the antenna base **803** may be 40 mm long between the feed and ground couplings **809** and **811** and 16 mm wide. Moreover, the PIFA antenna **801** may be elevated approximately 10 mm off of a ground plane of the printed circuit board **821**. In addition, a distance from the feed coupling **809** to the end of the long antenna segment **805** can be modeled at 72 mm.

In Figure 8b, current densities are simulated at 1.8GHz. As shown in Figure 8b, both low-frequency band and high-frequency band radiators may effectively radiate at high frequencies. Simulated voltage standing wave ratio (VSWR) responses for the PIFA antenna of Figures 8a-b without the presence of a user's finger are shown in the graph of Figure 8c. Simulated voltage standing wave ratio (VSWR) responses for the PIFA antenna of Figures 8a-b with the presence of a user's finger are shown in the graph of Figure 8d. In Figures 8c and 8d, low-frequency band markers are provided at 824 MHz and 960 MHz, and high-frequency band markers are provided at 1710 MHz and at 2350 MHz.

Of the PIFA antennas discussed above, the PIFA antennas of Figures 5a and 8a may provide the greatest bandwidth. Moreover, the PIFA antenna of Figure 8a may be relatively easy to tune to a desired frequency band because of the relative independence (for tuning purposes) of the two branches which may extend from the feed and ground couplings.

According to embodiments of the present invention, a PIFA antenna may have at least two antenna segments with a ½-wave (or greater) resonance, and one of the segments may act as an impedance match to obtain a relativley broad bandwidth. With two orthogonal segments, dual-band performance may be readily obtained with a relatively broad high-band response. Additional grounding points may be added along the branch with the RF feed to obtain a better VSWR response. In addition, multiple segments can be added to either antenna segment to obtain additional frequency resonances at additional operating bands.

In a particular product, a PIFA antenna according to embodiments of the present invention can be loaded with plastic with a dielectric constant of approximately 2 so that a size of the antenna may be reduced. Additional loading (and size reduction) may also be caused by a battery. In general, gain may decrease, but bandwidth may improve. Slight variations in the pattern may be seen due to the addition of shield cans, etc, as well as the size of the ground plane. With a PIFA antenna according to Figures 7a-b, relatively high gain may be provided in a band of frequencies between 1710 MHz and 2.4 GHz, so that the antenna of Figures 7a-b may be especially suited for use in a multiple mode mobile radiotelephone operating in frequency bands for DCS, PCS, and WCDMA communicaitons. A second resonance of the antenna may also be shifted so that BlueTooth frequencies (i.e. 2.4GHz to 2.485GHz) are also covered.

In the drawings and specification, there have been disclosed typical preferred embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation, the scope of the invention being set forth in the following claims.